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Decreases in atomic hydrogen over the summer pole: Evidence for dehydration from polar mesospheric clouds?

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[1] Observations from the Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) instrument on the NASA/Thermospheric Ionosphere Mesosphere Energetics and Dynamics satellite show a surprising decrease in the inferred atomic hydrogen (H) over the polar regions in the lowermost thermosphere during the summer. This contrasts with predictions by global models that H should peak in this region at this time. We suggest the decrease is a consequence of the sequestering of the water vapor by the formation of polar mesospheric clouds (PMCs) that redistributes the H_2O thus reducing the chemical source of H. This decrease is more pronounced in the Northern rather than the Southern summer which is roughly consistent with the known morphology of PMCs. A model calculation which includes a PMC parameterization gives good qualitative agreement with the data suggesting that this process should be considered in global models of the coupling between the middle and upper atmosphere. **Citation:** Siskind, D. E., D. R. Marsh, M. G. Mlynczak, F. J. Martin-Torres, and J. M. Russell III (2008), Decreases in atomic hydrogen over the summer pole: Evidence for dehydration from polar mesospheric clouds?, *Geophys. Res. Lett.*, *35*, L13809, doi:10.1029/2008GL033742.

1. Introduction

[2] Interest in the high latitude summer mesopause and in particular polar mesospheric clouds (PMCs) has greatly expanded in recent years. One of the questions PMC researchers are addressing is how the formation of PMCs feeds back to influence the clouds' chemical and radiative environment. For example, *von Zahn and Berger* [2003] suggested that the persistent dehydration associated with condensation of water vapor could have an effect on radiatively active constituents such as ozone. We recently showed that ozone appeared to be enhanced above regions of PMCs, presumably due to the anticorrelation of HO_x (which would be reduced) and O_x [*Siskind et al.*, 2007].

[3] Direct measurements of the predicted dehydration are not available because of the difficulty of making H_2O measurements at 85–90 km even when nominal water abundances are present. As an alternative, we here present the first results from the TIMED/SABER observations of atomic hydrogen. Hydrogen (H) data are inferred from SABER measurements of the vibrationally excited hydroxyl airglow, ozone and temperature. We show that the SABER data agree well with historical datasets and then compare the data with the Whole Atmosphere Community Climate Model (WACCM). At mid-latitudes both the observations and the model show a maximum of H in the summer. However, at high latitudes (75°), while the model continues to show a summer maximum, the data show a precipitous decrease as the summer season progresses. We suggest that the likeliest explanation for this is the sequestering of the H_2O source of H by condensation onto PMC ice clouds. Finally we show that the morphology of these summertime H bite-outs is generally consistent with both the known morphology of PMCs and with a global model that includes a PMC parameterization

2. Overview of SABER Atomic Hydrogen Inferences

[4] SABER is a 10 channel broadband, limb-viewing, infrared radiometer which has been measuring the stratospheric and mesosphere since the launch of the TIMED satellite in December 2001. Atomic hydrogen is not measured directly, but rather, is inferred from a combination of the OH* Meinel band airglow at 2.0 μm, the ozone measured at 9.6 μm, and the temperature and pressure which are obtained from the 15 μm emission of CO_2. The OH* data have been published by *Marsh et al.* [2006] while a validation paper for the ozone and the hydrogen data is currently in preparation. The high altitude temperature data, retrieved using an algorithm which accounts for non-LTE were first discussed by *Mertens et al.* [2004]. We use the most recent processing (V1.07) which yields significantly improved temperature retrievals at high latitude summer as described by *Kutepov et al.* [2006].

[5] The specific approach to infer H from the above cited emissions is based upon *Mlynczak et al.* [1998]. As they discuss, the excitation of the OH* Meinel bands results from the reaction of $H + O_3$. SABER specifically observes emission from the $\upsilon = 8$ and 9 vibrational levels which are populated directly upon the reaction of H and ozone. Thus the H is proportional to the OH* emission and inversely proportional to the ozone. Of course, there are numerous potentially uncertain kinetic parameters that describe the physical quenching and radiative emission of the vibrationally excited OH molecule. Among these are the reaction rate coefficient for $H + O_3$ (including its value at low temperatures), the magnitude of the quenching, particularly by atomic oxygen (discussed in more detail below), the values

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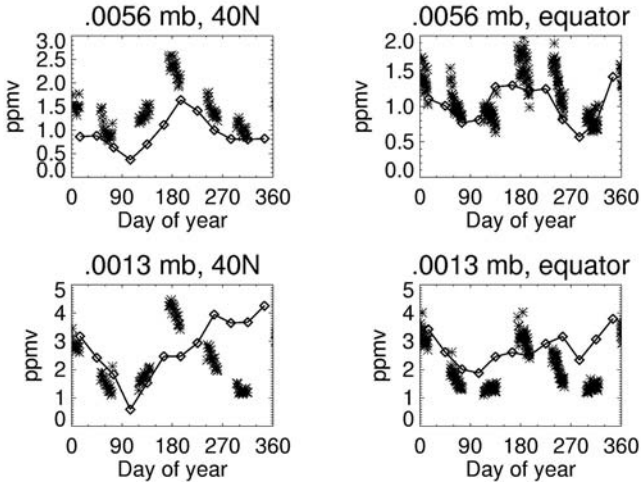

Figure 1. SABER H (stars) for 1200–1600 LT compared with SME H (solid lines and diamonds) data tabulated by *Thomas* [1990]. The SABER H were processed using a value for the OH* + O quenching of 2×10^{-10} cm^3 s^{-1} which corresponds to the medium quenching used in Figure 2 (see text).

of the Einstein A values (we use values derived from *Nelson et al.* [1990] which are in good agreement with a recent evaluation by *van der Loo and Groenenboom* [2007]) and as well as the measurement uncertainties in the 9.6 um ozone data and the atomic oxygen densities. A detailed evaluation of these uncertainties is in preparation; here, to demonstrate that our results are reasonable, we compare our results with the only previous satellite-derived inference of atomic hydrogen, from *Thomas* [1990] using Solar Mesosphere Explorer (SME) data. Figure 1 shows the seasonal variation of atomic hydrogen from SABER compared with the SME values. Since SME was in a fixed local time orbit of 1500 hours, we restricted the SABER data to the time range of 1200–1600 LT. The SME data are from *Thomas* [1990, Table 2] and the comparison is shown for two representative pressures. In general, given the large differences in the method used (for example, different OH Meinel emission bands), the agreement is quite good. Particularly at.0056 hPa, both datasets show an annual cycle at 40°N and a semi-annual cycle at the equator, with excellent agreement in absolute magnitude. The agreement is somewhat less good at 0.0013 hPa, with SME and SABER diverging after day 250 at 40°N. This may be a problem with the SME data since their values jump by a factor of 4 from the next level lower down (.0032 hPa) in Thomas' table; such large changes are not seen anywhere else in the SME data.

[6] At higher altitudes in our analysis, the uncertainties associated with atomic oxygen deserve particular mention. As an example, Figure 2 shows daily averaged vertical profiles from 2005 for two latitudes, 35°N and 75°N. The vertical range of the inferred H roughly brackets the bulk of the OH* emission layer. Six curves are shown in both Figures 2a and 2b, three for three different values of the quenching of OH* by O, for two different days, day 150 (solid lines) and day 180 (dashed lines). As we will discuss, the choice of days is important because Day 150 is before the Polar Mesospheric Cloud seasons, Day 180 is near the middle of the season. The three quenching values are 5×10^{-13} cm^3 s^{-1} (essentially no quenching by O [e.g., *McDade and Llewellyn*, 1988]), 2×10^{-10} cm^3 s^{-1} (based upon an extrapolation of the result of *Spencer and Glass* [1977] for v = 1 deactivation) and a newly reported higher value of 4×10^{-10} cm^3 s^{-1} from *Copeland et al.* [2006, also personal communication, 2006]. At 35°N, the effect of O quenching uncertainties are large above 0.001 hPa. This is because the O concentration we use, which is inferred from SABER, can approach 10^{12} cm^{-3}. For such large O, a large quenching rate would potentially require much more H to produce the OH* emission we observe and thus the inferred H becomes quite high. At 75°N, both the inferred SABER O and also O from the NRLMSIS model are much lower, below 2×10^{11} cm^{-3}. Thus the inferred H is much less sensitive to the uncertainty in the quenching. Of particular interest for this paper is the fact at 75°N, the H on day 180 is consistently smaller than on day 150, the reverse of what is seen at 35°N. This is a robust result despite the uncertainties associated with atomic oxygen quenching. Also shown in Figure 2 is 10-day averaged

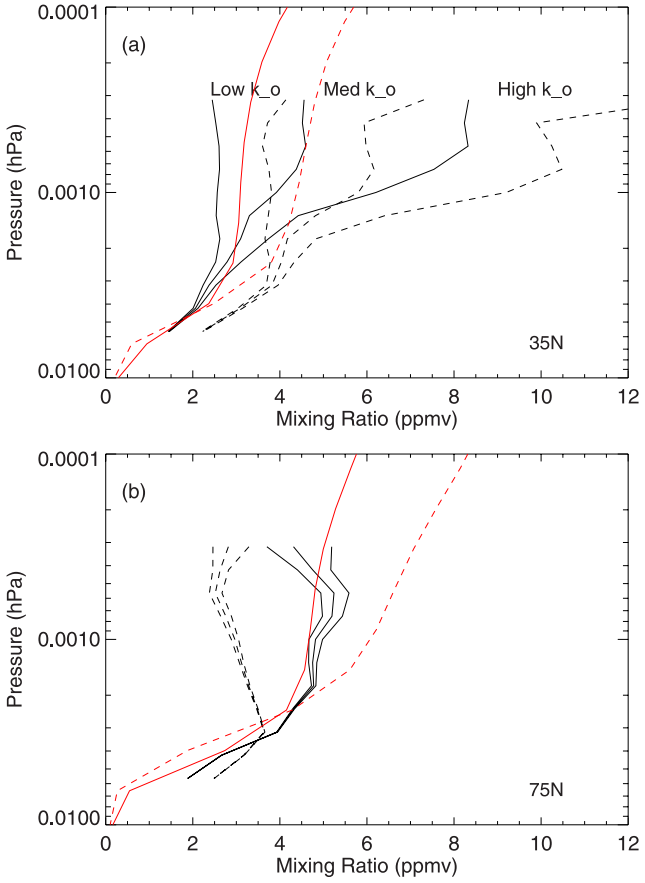

Figure 2. Daily averaged altitude profiles of SABER H for two days in 2005, day 150 (solid curves) and day 180 (dashed): (a) 35°N and (b) 75°N. For each day, three curves are shown corresponding to low, medium or high values of the OH* + O quenching rate coefficient (see text). These are explicitly labeled for clarity in Figure 2a. In addition altitude profiles from the WACCM are shown with solid red curves for day 150 and dashed red curves for day 180.

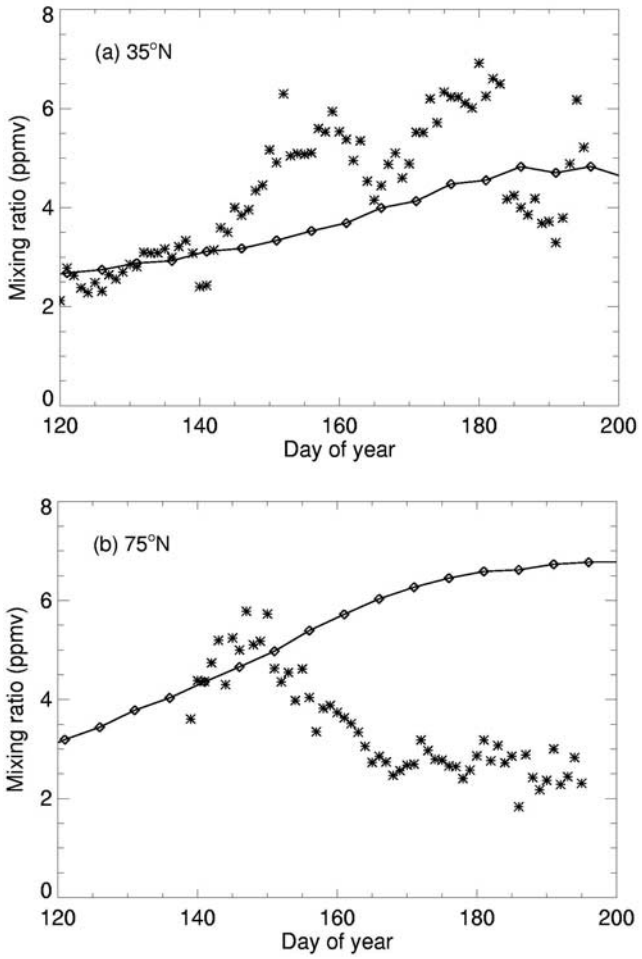

Figure 3. (a) SABER H (stars) (assuming an OH* + O quenching of 2×10^{-10} cm^3 s^{-1}) for 35°N and 0.00056 hPa (about 95 km) and WACCM calculations (solid lines with diamonds) for 34°N, 0.00053 hPa. (b) same as Figure 3a but for 75°N. Since SABER does not yaw to look at the Northern Hemisphere until the middle of May, the data do not start until day 139.

zonal-mean hydrogen from WACCM [*Marsh et al.*, 2007] for solar minimum conditions for Day 150 and Day 180. At 35°N, it shows more H on day 180 than day 150, in agreement with the data. At 75°N, the WACCM H shows the reverse of the SABER data.

3. Seasonal and Interannual Variations in H

[7] Figure 3 shows the seasonal variation of the inferred H at 35°N and 75°N for 2005 at 0.00056 hPa (near 95 km). Also shown are calculated zonal averaged H from the WACCM model at a similar pressure (0.00053 hPa). At 35°N, although there is much variability in the data, both data and model clearly show a steady increase through the period. SABER begins observing at 75°N after its yaw in the middle of May (around Day 135–140 for different years). After Day 150, the differences between data and model are quite dramatic. We note that *Thomas* [1990] did not report H data for such high latitudes so this result is new. Clearly some process is different at high latitudes that is not captured by the model. We suggest it is dehydration due to PMC formation. By removing the H_2O, the source of H atoms for the lower thermosphere is cut off and the H decreases instead of increases as predicted by the models.

[8] Figure 4 shows examples of SABER H variation for five other summer seasons, three for the NH (2002, 2005 and 2007) and two for the SH (2002/2003 and 2005/06) at 0.00056 hPa. Interestingly, SABER shows a similar magnitude of H decrease in 2007 as in 2005, but somewhat less in 2002. This is potentially significant since the mesopause was warmer in 2002 [*Goldberg et al.*, 2004] with less PMC [*Karlsson et al.*, 2007]; fewer PMCs might imply less dehydration and less H depletion. In addition, the H decrease is also somewhat smaller for the two SH periods (2002–03 and 2005–06). Again, this correlates with known PMC morphology which indicates fewer and dimmer clouds in the SH relative to the NH [*Bailey et al.*, 2005; *Hervig and Siskind*, 2006], thus implying less sequestering of the H_2O.

4. Predictions From a Global Model With Parameterized PMCs

[9] Figure 5 shows a comparison of a two dimensional chemical/dynamical model (CHEM2D) at 73°N just above the mesopause (0.00056 hPa), for a case which includes the PMC parameterization of *Siskind et al.* [2007] and for a baseline case with no PMCs. The model is output every 10 days. Also shown, for reference is the gas equivalent H_2O mixing ratio contained in ice [*Siskind et al.*, 2007, equation (2)] at 0.005 hPa which corresponds to the middle of the model PMC layer as well as the SABER H for 75°N (same as Figure 3b). PMC onset in the model is defined as occurring when the saturation ratio (= water vapor partial pressure over the saturation pressure for water over ice) exceeds 10. This threshold is met by Day 171 and thus the model begins to produce ice on that day (it does not become noticeable on Figure 5 until the model output on Day 181). Figure 5 shows that as the ice develops, the model H is depleted and instead of increasing into the summer, the

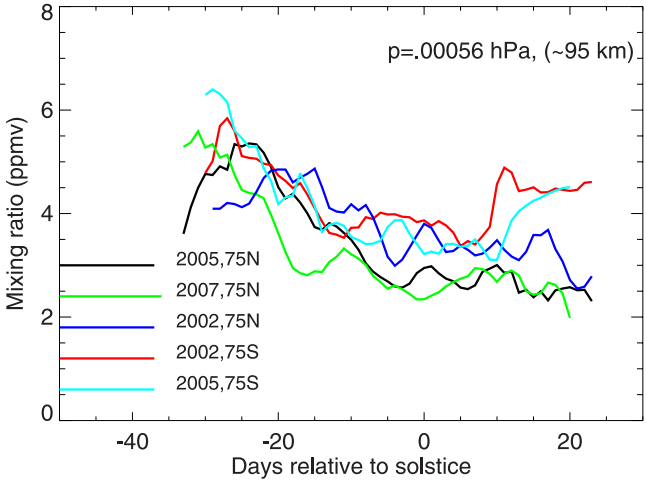

Figure 4. Daily variations in SABER H for 0.00056 hPa for five different summer seasons, three for the Northern Hemisphere and two for the Southern Hemisphere according to the color-coded label. The data are a 3 day smooth of a diurnal average.

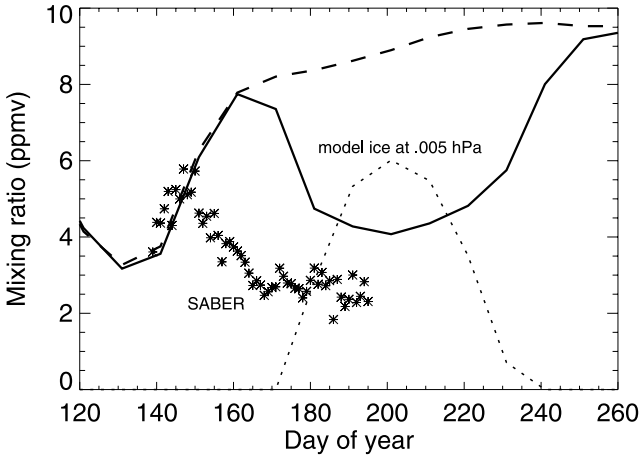

Figure 5. CHEM2D model calculations of seasonal variation of H at 0.00056 hPa (~95 km). Two curves are shown, one without any PMC parameterization (dashed) and one with the PMC parameterization of *Siskind et al.* [2007] (solid). The associated model ice mixing ratio at 0.0056 hPa (~83–84 km) is given as the dotted line. The SABER data from Figure 3b are also shown (stars).

model with parameterized PMC shows decreasing H. Note that SABER shows that the H begins decreasing almost immediately after yawing to the NH, much earlier than the model. New results from the Aeronomy of Ice in the Mesosphere (AIM) satellite (M. Hervig et al., SOFIE PMC observations during the northern summer of 2007, submitted to *Journal of Atmospheric and Solar-Terrestrial Physics*, 2008) now show that PMCs are ubiquitous at 90 km after late May (approximately Day 140). CHEM2D does not capture this early onset of PMCs and thus it is perhaps not surprising that the H decrease does not begin in the model until Day 171. The model shows that the H recovers to its non-PMC value after the ice disappears around Day 240.

5. Discussion

[10] We have shown an unexpected seasonal decline in atomic hydrogen inferred from SABER at high summer latitudes. This decrease, the opposite of what is suggested by models, is robust against uncertainties in the SABER H retrieval due to atomic oxygen kinetics. We suggest that the likeliest cause for the dramatic decrease in atomic hydrogen at polar latitudes is that it reflects the dehydration of the mesopause region from polar mesospheric clouds. Other possibilities were considered but found to be inconsistent with available evidence. For example, if there were significant upwelling during the summer at 0.00053 hPa that is not captured by WACCM, it might transport H-poor air upwards and lead to a decrease. However, SABER shows temperatures at and above the 0.001 hPa region to be generally increasing during the summer season (not shown). This corresponds to downwelling that would bring H-rich air down from the thermosphere. Thus a dynamical explanation appears inadequate. The H decrease is also unlikely to be of photochemical origin since the near constant sunlight coupled with increased H_2O at the mesopause leads to a large increase in H production from dissociation by solar Lyman alpha. Again, this would lead to the opposite seasonal behavior from observations. We are left with a microphysical explanation as the most likely one.

[11] This suggests some interesting new aspects in our understanding of the coupling between the middle and upper atmosphere. Models of the escape of hydrogen from the terrestrial atmosphere have consistently emphasized the importance of transport processes in the upper mesosphere and lower thermosphere over chemical effects [*Yung et al.*, 1989]. To date however, these studies have all been with one-dimensional models that cannot account for the strong seasonal and latitudinal effect we observe here. It would be interesting to reevaluate the flux of hydrogen containing species into the thermosphere with effects of microphysics considered in a multi-dimensional model.

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